Ocean Engineering 113 (2016) 215–223

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Detuning and wave breaking during nonlinear surface wave focusing

Dianyong Liu [a], Yuxiang Ma [a,*], Guohai Dong [a], Marc Perlin [b]

[a] State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, 116023 Dalian, China
[b] Department of Naval Architecture and Marine Engineering, University of Michigan, Ann Arbor, MI 48109, USA

ARTICLE INFO

Article history:
Received 6 February 2015
Accepted 26 December 2015
Available online 14 January 2016

Keywords:
Nonlinearity
Detuning
Wave breaking
Breaking position
Spectra
Energy dissipation

ABSTRACT

Using an energy focusing technique, several transient wave trains were generated in a two-dimensional wave flume to investigate their nonlinear evolution. By increasing the initial wave steepness (S_0), while all other parameters remained the same, non-breaking through breaking conditions were achieved. The experimental results demonstrated that the waves' initial steepness affected the focusing process significantly. As expected, the nonlinear effects on wave packets with a low initial steepness were very small. However, for cases with large initial steepness, nonlinearity increased causing the wave packet to focus and break prematurely, a “detuning” process. As a result of the detuning process more than one breaker may occur, and more importantly when this ensues, energy loss was altered. It is found that for $S_0 < 0.274$, only one breaker occurred, and the energy loss increased with increased initial steepness. For larger steepness, two breakers occurred and the total energy loss remained nearly constant ($\sim 17\%$) as the initial steepness was increased. As the initial steepness was increased still further, a large plunging breaking was obtained with additional energy loss (4%). These results suggest that the “detuning” has a pronounced influence not only on the resulting wave field, but on the resulting energy loss.

1. Introduction

Real sea waves often exhibit breaking on the ocean surface. Breaking represents a strongly nonlinear phenomenon encompassing different stages: incipient breaking, developing breaking, subsiding breaking and residual breaking (Babanin, 2011). The process limits the height of waves and dissipates wave energy, converting it into currents and turbulent kinetic energy (Drazen and Melville, 2009). In addition, theses currents and large impact forces before and at breaking have been long known to cause hazards to navigation vessels and marine structures (Smith and Swan, 2002). However, due to the complexity of the breaking process, a fundamental understanding of wave breaking has been elusive even though water waves have been studied scientifically for a very long time.

For several decades now, a significant effort has been devoted to the study of breaking waves (Babanin, 2009; Baldock et al., 1996; Benjamin and Feir, 1967; Clauss, 2002; Rapp and Melville, 1990; Thorpe, 1993; Tian et al., 2012; Tulin and Waseda, 1999; Wu and Nepf, 2002; Wu and Yao, 2004; Zhang and Melville, 1990). Laboratory experiments, which can be conducted in a well-controlled environment, are a popular method wherein high-precision measurements can be obtained to further our understanding of the dynamics and kinematics of wave breaking. On the other hand, the complexities associated with breaking waves make detailed numerical simulations or theoretical analysis very difficult. Likewise, field measurements of breaking waves are problematic due to the difficulty of measuring accurately the appropriate parameters in intermediate and deep water.

As regards lab experiments, there are three primary methods used for generating breaking waves. The first method, which is appropriate for shallow water breaking, is via shoaling, where waves propagate toward a beach and wave height increases until breaking occurs (Mukaro et al., 2013). The second method takes advantage of frequency dispersion, and generates waves that near a prescribed spatial position (Kway et al., 1997; Rapp and Melville, 1990; Yao and Wu, 2005), while the third technique uses the modulation instability (Babanin et al., 2007; Benjamin and Hasselmann, 1967; Longuet-Higgins, 1978). The first method is used to study near-shore breaking while the other two techniques are employed in the study of intermediate and deep water wave breaking. In this study, in the presence of intermediate and deep water, the method of dispersive focusing in a laboratory flume was adopted.

In view of the many important investigations of wave breaking (see Perlin et al. (2013) for a recent review), the prediction of the breaking onset of surface waves is crucial. Various threshold criteria for predicting the onset of breaking have been proposed, for example based on wave geometry (i.e. wave steepness, vertical/horizontal asymmetry, etc.), kinematics (i.e. crest fluid velocity) and dynamics (i.e. downward acceleration at the wave crest, local energy growth

* Corresponding author.
E-mail address: yuxma@dlut.edu.cn (Y. Ma).

http://dx.doi.org/10.1016/j.oceaneng.2015.12.048
0029-8018/

rate, etc.). Intuitively, the criterion based on crest fluid velocity (i.e. a kinematic breaking criterion) is perhaps the simplest notion, i.e. if the horizontal crest particle velocity U exceeds the wave phase speed C, wave breaking occurs. However, the application of this criterion is non-trivial because of the difficulties associated with measuring U and C during the rapidly evolving breaking process. Regardless, kinematic criteria have drawn much attention. Particle image velocimetry (PIV) was used by Perlin et al. (1996) to measure the crest particle velocity U of plunging waves demonstrating that wave breaking had occurred when U/C reached 0.74. Stansell and MacFarlane (2002) investigated two different types of breaking waves and found that when plunging occurred U/C was equal to 0.81, while it was 0.95 for spilling waves. These investigations illustrated that the kinematic criterion seems inappropriate as a robust predictive standard. In addition, Oh et al. (2005) conducted experiments to detect breaking in deep-water in the presence of strong wind. They concluded that the kinematic criterion is also inadequate for predicting breaking under strong wind.

Compared to the study of the geometric criteria predicting breaking onset, criteria based on the evolution of the local energy have achieved better results. Song and Banner (2002) proposed a dimensionless local energy growth rate $\delta(t)$ to predict the onset of breaking waves through numerical study. This predictive parameter reflects the steepness of the maximal carrier waveform associated with the increased local carrier wave number. A threshold range for $\delta(t)$ of $(1.4\pm0.1)^{*}10^{-3}$ was suggested to distinguish wave breaking from non-breaking. Thereafter, a detailed laboratory experiment with the same initial conditions as Song and Banner's numerical study was conducted by Banner and Peirson (2007). This study substantiated the proposed breaking threshold. Then, Tian et al. (2008) evaluated the breaking criterion experimentally by different wave groups in a two-dimensional wave tank. It was found that the breaking criterion of Song and Banner (2002) is sensitive to the choice of the local wave number; they suggested that the local wave number should be determined from the breaking crest. However, this wave breaking criterion is difficult to apply, especially for the estimation of the local wave energy density. Recently, a further simplification of the diagnostic parameter proposed by Song and Banner (2002) was investigated and confirmed to provide a good approximation by Tian et al. (2010). Hence, this simplified approximation is used herein.

As has been clearly established by researchers, wave breaking plays a dominant role in dissipating the energy of ocean surface waves. Although significant effort has been expended to estimate the energy dissipation due to breaking via field and laboratory experiments, our present understanding of the energy dissipation resulting from wave breaking is far from adequate. Rapp and Melville (1990) systematically studied breaking waves in deep water by the dispersive focusing technique and estimated the energy dissipation by measuring the surface elevation upstream and downstream of breaking. They reported that during breaking the spilling process could dissipate 10% of the initial energy, while this value was 25% for the plunging case. Specifically, they found that the energy dissipation was from mostly the high end of the first harmonic band ($f/f_p=1-2$; f_p is the spectral peak frequency). Later, Kway et al. (1997) investigated deep-water breaking generated by focusing wave groups with three different spectral shapes and found that the energy losses varied from 14% to 22% for different spectral distributions. The so-called Hybrid Wave Model (HWM) was used to eliminate the bound wave components from measured surface elevations by Meza et al. (2000) in their investigation of energy dissipation; this illustrated that the energy dissipation is almost exclusively from wave components at frequencies higher than the spectral peak frequency (wave components below the peak frequency gained a small portion ~ 12% of energy). Wu and Yao (2004) investigated the energy dissipation of breakers on currents and showed that, in the presence of a strong opposing current, most of the dissipated energy in the higher frequency wave components transferred to the lower frequency band.

As mentioned above, a majority of studies on wave breaking that are undertaken in the laboratory use a computer-controlled wave-maker to focus an isolated breaking wave at a prescribed location by moving that position in space or in time according to superposition using linear theory. As one adjusts the steepness of the wave train, nonlinearity causes the temporal/spatial location to change. However, the evolution of this process and the subsequent dissipation that occurs is not clear. Recently, a study of weakly three-dimensional breaking by Liu et al. (2015) found that the breaking occurred prematurely compared with the linear focusing position. (This is not surprising as nonlinearity in gravity waves causes the wave speed to increase, and has been noted by others for two-dimensional experiments.) They attributed it to the focusing wave components "detuning", which is a nonlinear phenomenon that inhibits wave components from focusing at one location/time simultaneously, thus forming a large breaking wave. When relatively low-frequency wave components overtake relatively high-frequency wave components upstream of the prescribed focusing location, premature breaking may occur. More importantly, the remaining energy in the various wave components will continue to interact, and may cause a second breaker to occur during the "detuning" process. (In fact, for shallow water, this detuning phenomenon has been studied numerically by Pelinovsky et al. (2000) using the Korteweg–de Vries equation.) Therefore, it is necessary to investigate “detuning” during wave focusing in laboratory experiments. In experimental programs, wave groups are forced often from non-breaking through breaking by increasing the initial wave steepness.

In this manuscript, we investigate the detuning process in two dimensions. The paper is organized as follows: subsequent to the introduction, the experimental facilities and the wave generation technique are described carefully; then, the experimental results and observations are shown in Section 3; and lastly, the conclusions are presented.

2. Experiments

2.1. Experimental facility

The experiments were conducted at the State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, China. The experimental setup is shown in Fig. 1. This flume is 50 m long, 2 m wide and was used with a water depth of 0.6 m. A piston-type wave-maker is installed at one end of the flume, and in the following $x=0$ m is defined as the mean position of the

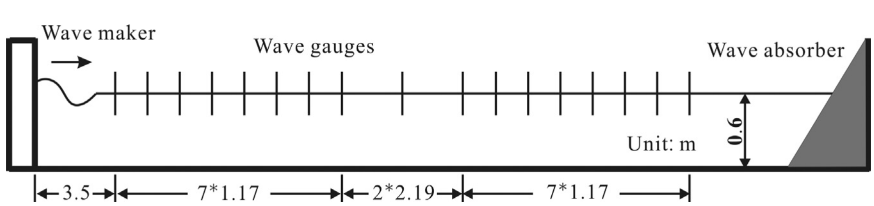

Fig. 1. Experimental setup.